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THE CALCULATION OF ROLL SEPARATING FORCES USING FLOW STRESS DATA OBTAINED ON THE CAM PLASTOMETER

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THE CALCULATION OF ROLL SEPARATING FORCES USING FLOW STRESS DATA OBTAINED ON THE CAM PLASTOMETER

by

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ABSTRACT

The predictive ability of two models of hot rolling, Orowan and Sims, have been examined. A plain carbon steel was rolled on the fully instrumented rolling mill at PMRL and the roll separating force for each pass was recorded. This steel was also tested on the Cam Plastometer over the ranges of temperatures and strain rates which occurred during rolling. The flow-stress data collected was then used in the two models to calculate the roll separating force for each pass.

The measured and calculated values of roll separating force were not in agreement over the whole range of rolling conditions used in these tests. It was found, however, that $\frac{P_{meas}}{P_{calc}}$, the ratio of the measured roll-separating force to the calculated value varied as a function of the ratio, $\frac{L}{h}$, of contact length to average plate thickness during the pass. Irrespective of whether the Orowan or the Sims theory was used to calculate the roll-separating force, a strong correlation was obtained. These results emphasize the importance of roll-pass geometry in determining mill loads and in predicting industrial data from laboratory tests.

INTRODUCTION

The analysis or planning of hot working schedules is difficult without information on the resistance of metals to deformation at high temperatures and strain rates. This information is of particular importance to the steel industry because of the generally high mill loads required to roll modern HSLA steels and the influence of scheduling on the final metallurgical and mechanical properties. To avoid the expense of plant trials, universal testing systems have been developed to simulate the hot-rolling process. The required data can be obtained by several methods, including tension, torsion and axisymmetric compression. Of these, the Cam Plastometer is a unique compression-testing machine because it imparts deformation at a strain rate which is constant and over a significantly greater range ($1\text{-}250s^{-1}$) than can be obtained on most other testing machines.

After the flow stress of the material has been determined at the appropriate strain rates and temperature, this data must be translated into information about a specific process such as the hot rolling of plate. The translation is made through mathematical models which are based on an analysis of the mechanics of the process. Two such models for calculating roll force from flow-stress data were chosen, the first was developed by Orowan (1) and the second by Sims (4). Orowan's model was chosen because it is considered to be the most comprehensive and makes the minimum of assumptions. The Sims analysis on the other hand, makes several simplifying assumptions which facilitate the calculation of roll force and torque. Consequently, the Sims equations are used frequently in industry where calculations must be done quickly. The validity of a particular model can only be assessed from accurate flow-stress data and roll force measurements. The Physical Metallurgy Research Laboratories of CANMET have the necessary facilities to measure both of these quantities: (1) A 457 mm reversing mill which is instrumented to record mill-drive power, roll-separating force and roll-gap setting continuously during rolling (2) A Cam Plastometer for the measurement of the high temperature flow stresses of a material at strain rates between $1s^{-1}$ and $250s^{-1}$.

This report compares the ability of the Orowan model and the Sims model to predict roll separating forces using high temperature flow stress data obtained on the Cam Plastometer. To eliminate the complications brought about by the precipitation occurring in microalloyed steels, a plain C-Mn steel was selected for this study.

EXPERIMENTAL

An ingot of steel, whose composition is given in Table 1, was cast in the PMRL foundry and cropped to dimensions of 152 x 171 x 122 mm. The steel was then heated to 1220°C, soaked for 2 h and rolled according to the schedule (temperature and nominal entry thickness) shown in Table 2. The temperature was recorded by a thermocouple inserted into the centre of the ingot.

Cam Plastometer specimens, 19.6 mm in height and 12.7 mm in diam, were machined from the rolled plate. The samples were placed for 1 h in a furnace set at the test temperature and then transferred to the Cam Plastometer for testing. The load is recorded continuously during testing and the strain profile during the test is calculated from a knowledge of the rotational speed of the cam and its profile. Details of the operation of the Cam Plastometer have been reported elsewhere (3). Measurements were made at strain rates of $2s^{1}$ and $20s^{1}$ and showed that up to a two strain of 0.2, there is a small dependence of 1 low stress on strain rate. Therefore, in the calculation of roll forces, the flow stress data determined at $2s^{1}$, which approximates the strain rates in the rolling tests, Table 2, were selected.

The roll force predicted by the Sims model was calculated using the equation:

$$P = \bar{k}\sqrt{R' \delta}\, Qp \qquad (1)$$

$\bar{k}$ is the mean yield stress in plane strain

R' is the flattened roll radius

δ is the draft

Qp is a geometric factor dependent on the reduction and the ratio of R' to exit thickness.

The Orowan analysis has been adapted for calculation by computer by Hockett and the resulting program has been modified to run on the CANMET CYBER 730 (5).

RESULTS

The data collected during rolling is summarized in Table 2. A plot of roll separating force for each pass is shown in Fig. 1. The Cam Plastometer flow stress measurements are shown in Fig. 2. Each curve was fitted to the equation

$$\ln \sigma = A + B \ln \varepsilon$$

where σ is the measured flow stress
ε is the true strain
A and B are constants

These curves were fitted up to a maximum strain of 0.2 using linear regression analysis. The resulting equations and the respective correlation coefficients are listed in Table 3. These equations were then used in either the Orowan model or the Sims model for the calculation of roll force. The calculated values of the roll force, based on these flow stress equations, are compared to the measured values in Table 4. The temperatures used in these calculations are the average temperatures of the ingot, not the temperature at the centre of the ingot as shown in Table 2. Measurements of temperature at various points between the centre and the surface of the ingot have shown that a large temperature gradient exists (6). These measurements were used to calculate the average ingot temperature shown in Table 2.

DISCUSSION

It is evident from Table 4 that neither the Sims nor the Orowan analysis predict the roll pressure accurately over the entire range of rolling conditions used in this study. However the Orowan analysis does predict roll pressures that are significantly closer to the measured values than the pressures predicted by the Sims analysis.

The agreement for both analyses is relatively poor in the early passes. The assumption that is made in both analyses, that the forces at any point on a vertical plane perpendicular to the rolling direction are equal, is not valid when the length of the arc of contact is less than twice the

mean thickness of the stock in the roll pass (1). Because of this inequality of forces on a given plane, the material will experience a strain greater than that required to effect the overall reduction of the pass. This redundant shearing (11) requires more work than is required for homogeneous deformation and reduces the efficiency of the rolling process. As $\frac{L}{\bar{h}}$, the ratio of the contact length to the mean thickness in the roll pass, decreases the amount of redundant shearing and work increases. Also, as $\frac{L}{\bar{h}}$ becomes less than one the longitudinal stresses in the centre of the stock change from compressive to tensile. Therefore, at small $\frac{L}{\bar{h}}$, at which values the longitudinal tensile stresses become substantial, rolling will not be as effective at removing cast structure (porosity, segregation) and the tensile stresses can lead to cracking (12).

Prandtl has calculated the pressure required for compression of an ideally plastic material under conditions of plane strain (7). The results from this analysis, which does not assume homogeneous deformation, show that, as $\frac{L}{\bar{h}}$ decreases below unity, the mean pressure required can increase up to a maximum of 2.57 times the yield stress in axisymmetric compression. In the centre of the block, tensile stresses can be as large as the yield stress of the material (1).

Various methods have been used which avoid the inadequacies of the slab method used by Orowan and Sims (1,8,9). The results of these analyses are in agreement with respect to the variation in the roll pressure with the ratio of contact length to material thickness. The results of a treatment by Green and Wallace (8) indicate that the roll pressure can be expressed by the equation:

$$P = \bar{k}\left(L\,\frac{\bar{h}}{2L} + \frac{L}{2\bar{h}}\right) \qquad (2)$$

P is the specific roll pressure MN/cm

$\bar{k}$ is the mean yield stress in plane strain

L is the contact length

$\bar{h}$ is the mean thickness $(h_1 + h_2)/2$ in the roll pass

This equation has been plotted in Fig. 4 and 5 as $\frac{P}{kL}$ versus $\frac{L}{\bar{h}}$ as proposed by Green and Wallace (8). Also plotted is the ratio of the measured pressure to the value calculated by either of the Orowan or Sims analysis. Figures 4 and

5 also include data (schedules 2, 3 and 4) from other recent tests conducted in this laboratory (13). This plot shows that by using the geometric factor $\frac{\bar{h}}{2L} + \frac{L}{2\bar{h}}$ the roll pressure calculated by the Orowan method can be brought into good agreement with measured values when $\frac{L}{\bar{h}} > .375$. The same can be said for the Sims method, however the geometric factor dependent on $\frac{L}{\bar{h}}$, would be larger than the one predicted by Green and Wallace (8).

As a final comparison between the Orowan and Sims methods various equations involving the parameter $\frac{L}{\bar{h}}$ were fitted to the data using the linear least squares method. The best equation examined is [based on the multiple correlation coefficient and the statistical F test (10)] of the form

$$\frac{P \text{ meas}}{P \text{ cal}} = A + B\frac{L}{\bar{h}} + C\frac{\bar{h}}{L} + D\left(\frac{L}{\bar{h}}\right)^2 \qquad (3)$$

P meas is the measured specific-roll pressure

P calc is the calculated specific-roll pressure using either the Orowan or Sims model.

A, B, C and D are constants determined by the method of linear least squares.

The results of the regression analyses, which demonstrate the suitability of these two equations as a predictive tool, are given in Table 5. Statistically, there is very little difference between the two equations and therefore it is concluded that the roll separating force as predicted from the Sims model is as accurate as that predicted using the Orowan model.

SUMMARY

A comparison of measured roll-separating force values with those calculated using equations developed by either Orowan or Sims shows that:

1. Calculated values do not agree with the measured values over the whole range of pass geometries used in this study.
2. There is a strong correlation between $\frac{P \text{ meas}}{P \text{ cal}}$, the ratio of measured roll-separating force and the calculated value with $\frac{L}{\bar{h}}$, the ratio of contact length to plate thickness.
3. The roll-pass geometry must be considered when predicting industrial results from laboratory tests.

4. Roll-separating forces predicted using the Sims model are as accurate as those predicted using the Orowan model.

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Table 1 - Alloy composition wt %

C	Mn	Si	S	P
.03	.62	.32	.014	.004

Table 2 - Rolling data

Pass No.	Centre temp °C	Ave temp °C	Entry thickness mm	True strain	Roll force MN/cm	Strain rate s^{-1}
1	1202	1182	122.2	.057	.0334	1.54
2	1177	1154	115.4	.113	.0442	2.20
3	1152	1122	103.1	.104	.0430	2.25
4	1127	1100	92.9	.115	.0443	2.48
5	1102	1082	82.8	.129	.0494	2.78
6	1055	1035	72.8	.113	.0454	2.77
7	1000	992	65.0	.121	.0513	3.04
8	955	947	57.6	.135	.0581	3.43
9	902	902	50.3	.114	.0512	3.33
10	852	852	44.9	.115	.0547	3.59
11	822	822	40.0	.056	.0284	2.65

Final thickness = 37.82 mm

Table 3 - Regression coefficients for the flow stress equation $\sigma = A\,\varepsilon^{B}$

Temp °C	A	B
1200	4.73	.392
1100	5.15	.409
1000	5.43	.404
900	5.63	.383
800	5.81	.379

Table 4 - A comparison of measured and calculated roll separating forces

Pass No.	Specific roll force, MN/cm			$L/\bar{h}$	Roll force ratio Meas/Calc	
	Measured	Calculated				
		Orowan	Sims		Orowan	Sims
1	.0334	.0177	.0130	.340	1.89	2.23
2	.0442	.0331	.0260	.490	1.33	1.48
3	.043	.0331	.0253	.501	1.30	1.37
4	.0453	.0366	.0283	.556	1.24	1.39
5	.0494	.0417	.0318	.627	1.18	1.35
6	.0454	.0399	.0303	.624	1.14	1.30
7	.0513	.0450	.0348	.686	1.14	1.28
8	.0581	.0540	.0412	.786	1.08	1.23
9	.0512	.0475	.0365	.758	1.08	1.22
10	.0547	.0514	.0394	.819	1.06	1.21
11	.0284	.0282	.0209	.626	1.00	1.18

Table 5 - Results of regression analyses

Roll theory	Regression equation	Multiple correlation coefficient	F_{calc}	F_{table}	$\frac{F_{calc}}{F_{table}}$*
Sims	$\frac{Pmeas}{Pcalc} = -1.57 + 2.83 \frac{L}{\bar{h}} + 3.54 \frac{\bar{h}}{L} - 1.57\left(\frac{L}{\bar{h}}\right)^2$	.952	151	4.82	31.3
Orowan	$\frac{Pmeas}{Pcalc} = -1.25 + 2.29 \frac{L}{\bar{h}} + 2.74 \frac{\bar{h}}{L} - 1.29\left(\frac{L}{\bar{h}}\right)^2$	.942	126	4.82	26.1

* An F-ratio, $\frac{Fcalc}{Ftable}$, greater than 4 indicates that a model is a good predictive tool (10).

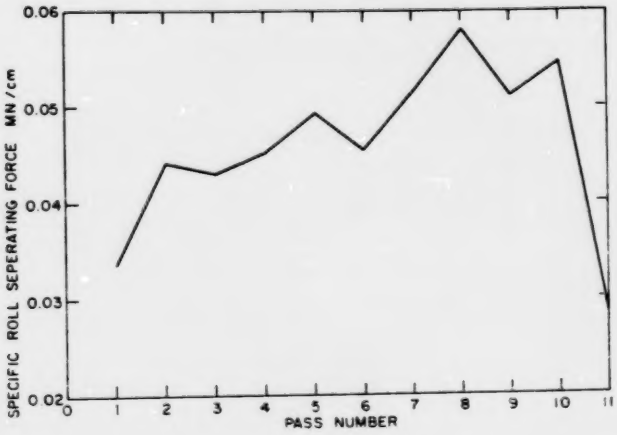

Fig. 1. Roll seperating force. (neg 8112)

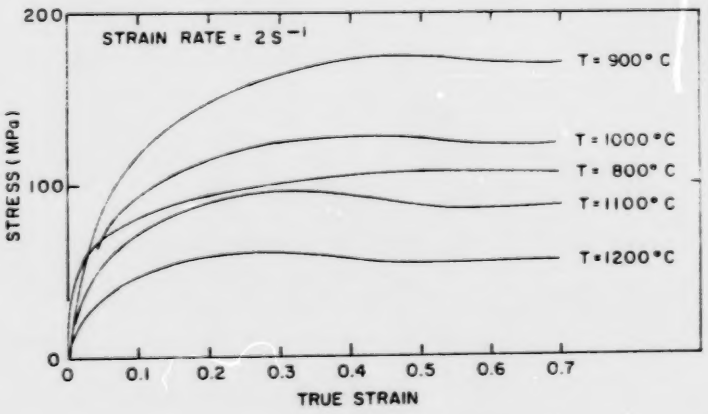

Fig. 2. Camplastometer flow stress measurements. (neg 8113)

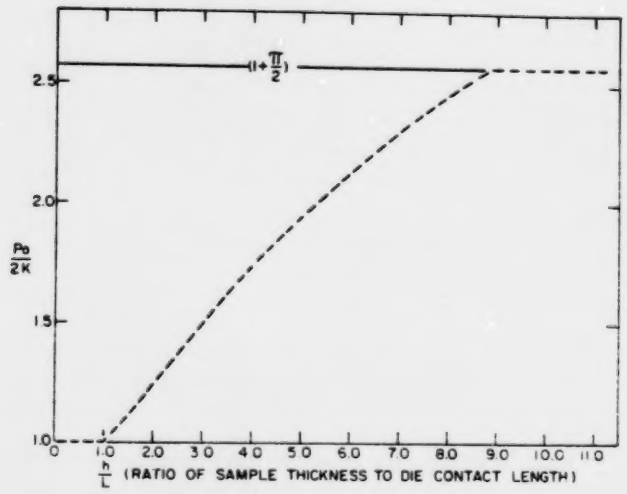

Fig. 3. Plot of the ratio of measured pressure to the flow stress in plane strain as a function of L/H. (neg 8115)

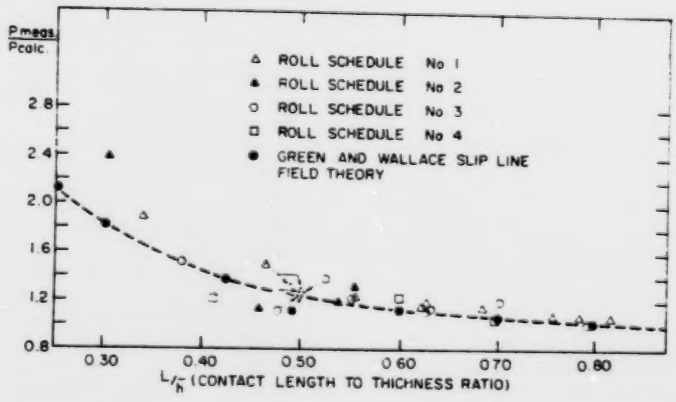

Fig. 4. Plot of the ratio of measured roll seperating force to the calculated value (Orwan's equation). (neg 8114)

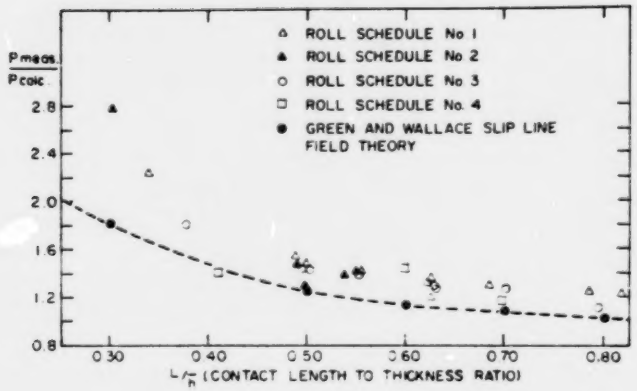

Fig. 5. Plot of the ratio of measured roll seperating force to the calculated value (Sims' equation). (neg 8116)